2C or Not 2C?

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Highlights

> The paper proposes simple visualizations of the challenge posed by the 2°C target.

> It shows how key assumptions influence the achievability of the target.

> It disentangles the points of deep uncertainty underlying the absence on consensus on the achievability of the target.

> It proposes an "uncertainties and decisions tree", linking different beliefs on climate change to various policy options.

Abstract

Political attention has increasingly focused on limiting warming to 2°C. However, there is no consensus on both questions "Is the 2°C target achievable?" and "What should be done with this target that becomes increasingly difficult to achieve?". This paper aims at disentangling the points of deep uncertainty underlying this absence on consensus. It first gives simple

visualizations of the challenge posed by the 2°C target and shows how key assumptions (on the points of deep uncertainty) influence the answer to the target achievability question. It then proposes an "uncertainties and decisions tree", linking different beliefs on climate change, the achievability of different policies, and current international policy dynamics to various options to move forward on climate change.

Keywords : feasibility of 2°C target, climate change negotiations, deep uncertainty

1. Introduction

According to the United Nations Framework Convention on Climate Change (UNFCCC), the ultimate goal of international climate policy is to "avoid dangerous anthropogenic interference with the climate system" (article 2). Defining a dangerous level implies making subjective choices and value judgments and any such choice cannot be based on scientific and technical evidence only; it has to be a political choice. Following the European Union's position, political attention has increasingly focused on limiting warming to 2°C. This target was recognized by the Major Economies Forum on Energy and Climate in L'Aquila, Italy, in July 2009; was explicitly included in the Copenhagen Accord; and is present in the final text adopted in Durban in December 2011.

However, to date the only mitigation commitments accompanying this target are the so-called Copenhagen pledges, and these pledges appear to be inconsistent with the 2°C objective (Rogelj *et al*., 2010; UNEP, 2010; Meinshausen *et al., 2009*). There is no definitive answer on whether this inconsistency can or should be resolved and diverging opinions on this question have been expressed more or less explicitly. It appears that some believe that the 2°C target is still reachable, and that the gap between this target and the sum of countries commitments can be bridged with more ambitious policies. For instance den Elzen and Roelfsema (2011) identify options to close the gap between Copenhagen pledges and the 2°C target. They also indicate there are important risks that could widen the gap. And more and more researchers express doubts, more or less explicitly, about the feasibility of the target. For instance, Rogelj et al. (2011) conclude that "Without a firm commitment to put in place the mechanisms to enable an early global emissions peak followed by steep reductions thereafter, there are significant risks that the 2°C target, endorsed by so many nations, is already slipping out of reach." By shifting the question to "when temperature change will exceed 2°C?", Joshi et al. (2011) also suggest implicitly that there are little chances to remain below the target. Likewise, the doubts about the feasibility of the 2°C target motivated a symposium and a special issue in the Philosophical Transaction of the Royal Society on the topic "4 degrees and beyond" (New, 2011). A poll conducted by the Guardian also revealed that 86% (out of 200 researchers on climate change and related fields who responded) do not think the 2°C target will be achieved (Adam, 2009). However, there is little investigation of the policy implications of a target that is becoming increasing difficult to reach. On the one hand, even though the 2°C target had little chance to be reached, it may play the important role of stating what is desirable, and should therefore be kept as a symbolic target. On the other hand, a target losing its credibility may undermine the negotiation process, and, if so, the international community should set a new (higher) target.

The aim of this paper is to clarify the alternative assumptions underlying these diverging view points and to explicit their implications. The justification of the 2°C target itself is beyond the scope of this article. The interested reader may refer to Cointe et al. (2011) and Tol (2007). The first shows that the 2°C target has no clear origin and that its adoption is due neither to compelling scientific evidence nor to the negotiators' informed choice based on scientific data. The second claims that it is founded on thin arguments and seems rather unfounded from a scientific point of view. It should also be noted that, from an impact point of view, some argue that a lower level of global mean temperature increase should be targeted (for instance Hansen et al., 2008; Mann, 2009; Hansen and Sato, 2011).

The first section explores the issue of the 2°C target feasibility. It reckons it is not possible to give a definite answer to the feasibility question, which implies several points of deep uncertainty (the climate sensitivity, different world views in defining which level of emissions reduction stringency is acceptable, the possibility to have negative emissions in the long-term, etc.). Deep uncertainty is a situation in which analysts do not know or cannot agree on (i) models that relate key forces that shape the future, (ii) probability distributions of key variables and parameters in these models, and/or (iii) the value of alternative outcomes. In other terms, deep uncertainty is a risk that cannot be measured and reduced to an objective probability distribution. Therefore the section aims at providing the reader with elements to navigate the deep uncertainties involved in the judgment of the feasibility of the 2°C target. It gives simple visualizations of the challenge posed by the 2°C target and disentangles how key assumptions (on the points of deep uncertainty) influence the answer to the feasibility question. To do so, it uses stylized emissions trajectories and a simple carbon cycle and climate model to show the link between the peaking year of global CO_2 emissions and the stringency of emissions reductions that are necessary after the peak to achieve a given target. It shows how assumptions on (i) the climate sensitivity, (ii) the evolution of the radiative forcing from non-CO_2 gases, and (iii) the possibility to have negative net global emissions at the end of the century influence this link between the peaking year and the stringency of after-peak reductions. It further gives several points of references to judge these required emissions reductions. These points of reference correspond to alternative estimates of what is achievable: (i) historical experience (what has already been done in terms of emissions reduction), (ii) committed emissions (what emissions are “locked-in” if existing infrastructure is operated until the end of its lifetime), (iii) emissions pledges (what emissions reductions are already enacted by countries). The reader can chose which point of reference corresponds best, in his or her views, to a limit to what emissions reductions are achievable in the future; hence deduce how challenging the 2°C target is.

The second section proposes an “uncertainties and decisions tree”, linking different beliefs on climate change, the achievability of different policies, and current international policy dynamics to various options to move forward on climate change. This “uncertainties and decisions tree” first summarizes and organizes the deep uncertainty points involved in the question of the feasibility of the 2°C target that the first section highlighted. It then investigates what to do with a 2°C target that becomes increasingly difficult to achieve. It leads to two unsettled issues. First, we do not know if the inconsistency between the sum of countries’ emissions reductions pledges and the global 2°C target is damaging the UNFCCC process and ultimately the success of climate mitigation. Second, there is no consensus on the status of this target: Is it a binding commitment from the international community to the (current and future) world population? Or is it a non-binding symbolic goal to help international negotiations move forward? There is no scientific evidence or consensus to settle these issues; however the policy options strongly depend on the answers.

This article confirms that there is not enough scientific evidence to give a definitive answer to both questions “Is the 2°C target achievable?” and “What should be done with this target that becomes increasingly difficult to achieve?”, but it gives an organized overview of the deep uncertainties involved in answering these questions. It calls for further research on those uncertainties to gather more evidences. But it also argues that some decisions will inevitably involve subjectivity because of inherent irreducible uncertainty. In this respect, the article only aims at providing the reader with some new elements to make his or her own opinion.

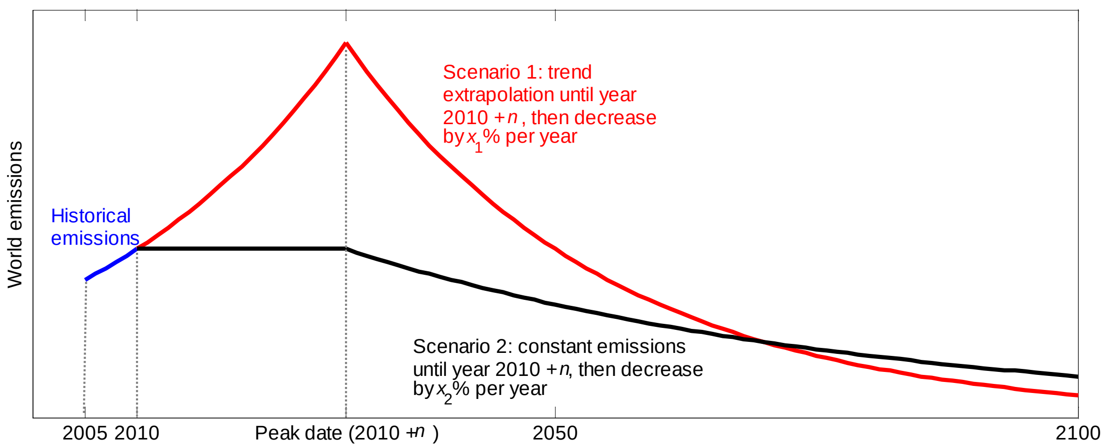
2. Visualizing the challenge

2.1. How much time do we have left?

To visualize the mitigation challenge, we explore the issue of global peaking of CO_2 emissions in light of the 2°C mitigation goal. The aim is to give the reader a sense of the stringency of mitigation actions required to reach the 2°C target depending on the peaking year, and to compare with historical emission trajectories, "committed" emissions from existing infrastructure and mitigation pledges. We use a simple carbon cycle and climate model to evaluate the global average temperature increase above pre-industrial levels implied by a family of alternative, idealized CO_2 emissions trajectories, combined with a fixed scenario for non-CO_2 gases and aerosols; see the Annex, and Figure 1. The trajectories are constructed so that global CO_2 emissions peak *n* years from 2010. Until then, emissions are assumed either (a) to grow at the mean annual rate of emissions growth observed during 2005–10 (Scenario 1); or (b) to be fixed at their 2010 level (Scenario 2), which already represents emissions reduction efforts. Note that emissions growth increased over the last decade except in 2009, when global emissions stabilized mainly because of the economic slowdown in countries of the Organisation for Economic Co-operation and Development. Considering a continued trend of emissions acceleration before they peak would lead to even more stringent requirement in terms of early peak date and emissions reductions after the peak. After emissions peak, the model assumes that ambitious mitigation action reduces global CO_2 emissions at a mean annual rate of *x* percent per year until 2100, which is taken as the end of the study horizon. The radiative forcing from other gases and aerosols follows the trajectory from the scenario Representative Concentration Pathway 3 Peak&Decline (RCP3-PD) from the IMAGE model (van Vuuren et al., 2011). This scenario is representative for the scenarios leading to extremely low greenhouse gas concentration levels in the literature. It represents a substantial reduction of greenhouse gases over time and is a best-case scenario with respect to non-carbon dioxide (CO_2) emissions, making our conclusion rather conservative.

To assess how realistic the 2°C objective is, Figure 2 shows the rate of global CO_2 emissions decrease (*x*) after the peak that is necessary to stay below a given temperature increase objective (here + 2°C and + 2.5°C) during the 21st century, assuming a climate sensitivity of 3°C. The figure shows that the required rate of CO_2 emission decrease is increasing nonlinearly with the peak year, underscoring the urgent need for action if the 2°C target is to be achieved.

Figure 1. Examples of Emission Trajectories, 2005–2100



For comparison purposes, the figure also reports as horizontal lines several points of reference. The 1.0 percent per year rate (horizontal line n°8) corresponds to the mean annual CO_2 emissions decrease from 2008 to 2020 necessary to achieve the target of -20% emissions in 2020 compared to 1990 level, announced by the European Union. This rate becomes 2.1 percent per year (horizontal line n°6) to reach the -30% target. The US pledge to reduce emissions by -17% in 2020 compared to 2005 corresponds to a 1.3 percent per year mean annual emissions decrease rate (horizontal line n°7). With world emission peaking after 2020, reaching the 2°C target would thus require – at the global level – CO_2 emission reduction efforts that are much larger than existing commitments by developed countries alone.

Historical experience also provides useful references. For instance, the 4.6 percent per year rate of mean annual CO_2 emissions reductions from 1980 to 1985 in France (horizontal line n°2) corresponds to the country's most rapid phase of nuclear plant deployment. According to WRI-CAIT data, it is the highest rate of CO_2 emissions reductions historically observed in any industrialized country over a five-year period, excluding the countries of the Commonwealth of Independent States during the years of economic recession that followed the collapse of the former Soviet Union. The French example is informative because it represents an important effort to shift away from fossil fuel energy and to decarbonize electricity production through the introduction of carbon-free technologies (in this case, the nuclear energy) and of energy efficiency measures. Even though motivations were different – reducing energy costs vs. reducing GHG emissions – and if future climate policies will likely be based on newer technologies and different economic instruments, this period provides an illustration of an energy transition similar in nature to what is needed to reduce GHG emissions.

From Davis *et al.* (2010), it can be calculated that committed emissions from existing energy infrastructure lead to a mean emission reduction pace of 5.7 percent per year (horizontal line n°1) during 2010–50 (middle scenario) and 4.3 percent (horizontal line n°3) (pessimistic scenario) if early capital retirement is avoided. In a comparable analysis that also takes the inertia in transport demand into account, Guivarch and Hallegatte (2011) find a mean decrease in committed emissions of 3.8 percent per year (horizontal line n°4) during 2010–50 (middle scenario) and 3.2 percent (horizontal line n°5) (pessimistic scenario). To go beyond this emission reduction rate, policies affecting new capital would not be sufficient, and early capital retirement or retrofitting would be necessary. Moreover, the limits to what is achievable in terms of emission reduction do not only depend on technical or economic criteria; political and social acceptability – linked in particular to the redistributive effects of climate policies – will also play a major role (Parry et al., 2005; Fullerton, 2008).

Figure 2. Rate of Emissions Reduction Necessary to Achieve the 2°C Target or a 2.5°C Target as a Function of the Peaking Year for Emissions, for climate sensitivity equal to 3°C. Only CO_2 emissions, including emissions from land-use, land-use change and forestry, are considered; the trajectory of radiative forcing from other gases is forced in this simple modelling experiment (see Annex). Historical emissions data are from CITEPA, WRI-CAIT and UNFCCC.

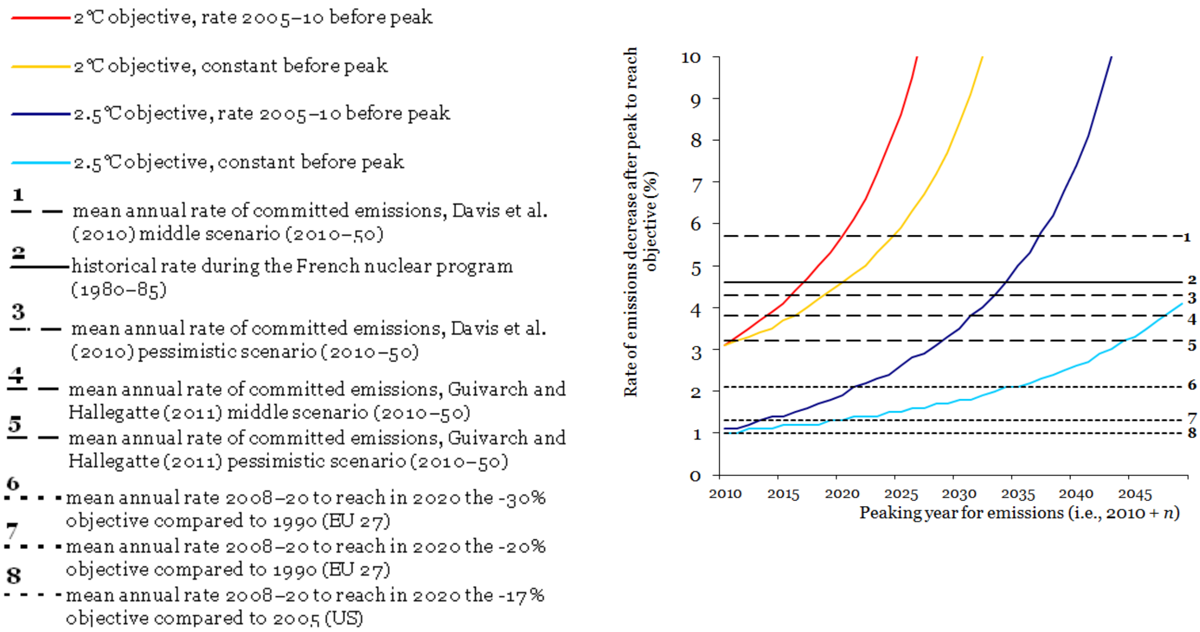


Figure 2 indicates that, for example, if one assumes that the climate sensitivity is equal to 3°C and that the maximum rate of emissions decrease is comprised between 3% and 4%, the 2°C target is achievable provided that the peak year occurs between now and 2018 (depending on the emissions trajectory before the peak). If one assumes that emissions can decrease at a higher rate, the peak year can occur later, but if one assumes that the maximum rate of emissions decrease is below 3%, then the 2°C target appears already out of reach.

The link between the peaking year and the stringency of emissions reductions necessary after the peak to reach the 2°C target are obviously affected by the uncertain climate sensitivity parameter. Figure 2 is based on the IPCC "best guess" (IPCC, 2007) for climate sensitivity, i.e. 3°C. Table 1 summarizes how the assumption on the climate sensitivity, in the range between 2°C and 4.5°C, influences the results. This range of sensitivities is chosen to give contrasted visions within the range of published estimates of the climate sensitivity probability distribution function. Note that no higher bound has been proposed for climate sensitivity, and published estimates of the climate sensitivity probability distribution function have a long right tail. 4.5°C thus cannot be seen as a higher bound for climate sensitivity. Table 1 shows that if climate sensitivity is around 2°C, and if, for example, emissions can decrease at a 3% annual rate, the 2°C target is achievable with an emission peak after 2040 if emissions between now and 2040 do not grow faster than between 2005 and 2010. But if climate sensitivity above 4°C, the 2°C target already appears to be unreachable.

Table 1. Influence of the climate sensitivity on the link between the peaking year of emissions and the rate of emissions decrease after the peak. The range of peaking years given in each cell corresponds to the cases when emissions before the peak continue to grow at the 2005-10 rate (resulting in the lower bound for the peaking year) and when emissions before the peak are constant (resulting in the upper bound for the peaking year). '--' symbol means that there is no solution, i.e. the peak should already have happened.

	rate of decrease after peak					
Climate sensitivity	1%	2%	3%	4%	5%	6%
2°C	2022-2061	2033-2072	2040-2076	2044-2079	2047-2080	2051-2082
2.5°C	--	2013-2015	2020-2028	2025-2035	2029-2039	2031-2042
3°C	--	--	--	2015-2017	2018-2022	2021-2026
3.5°C	--	--	--	--	--	2011-2012
4°C	--	--	--	--	--	--
4.5°C	--	--	--	--	--	--

It appears that there is no definite answer to the initial question of this section "how much time do we have left?", or in other terms "when should global emissions peak?", since there is uncertainty on the climate sensitivity and subjectivity in defining what is technically – but also economically, socially and politically - achievable. For example, if one assumes the climate sensitivity is close to 3°C, and that it is possible (technically possible but also economically, socially and politically acceptable) to reproduce at the global scale and over several decades the historical experience of emissions decreasing at 4.6%/ year in France over 1980-85, then we still have 10-15 years before global emissions have to peak to reach the 2°C target. If one assumes that the emissions reductions given in Copenhagen pledges are close to the highest achievable rate of global emissions decrease, then the 2°C target may already be out of reach, at least with a constant relative decrease in emissions after the peak and with the scenario of radiative forcing from non-CO_2 gases and aerosols assumed so far.

At this stage of this very simple illustrative exercise, it appears that, if climate sensitivity is not low, reaching the 2°C target would require global emissions to peak rapidly, in the coming decade or so. To investigate options to “buy time”, the next subsection explores an alternative scenario of radiative forcing from non-CO2 gases and considers the possibility of accelerating emission decreases, or even negative emissions, with a linear decrease in emissions (and thus possibly negative emissions).

2.2. Do we have strategies to “buy” time?

2.2.1. Buying time with measures on non-CO2 gases emissions?

To evaluate the sensitivity of the results to the assumption on non-CO2 gases radiative forcing trajectory, we reproduce the modeling experiment with an alternative assumption. The alternative trajectory is built from the rates of decrease or increase of non-CO2 radiative forcing in the RCP3-PD scenario (van Vuuren et al., 2011), assuming this rates are multiplied by 2 when they correspond to radiative forcing decreases and divided by 2 when they correspond to increases. Table 2 summarizes the results of this second experiment when efforts on non-CO2 gases are “doubled” compared to RCP3-PD. The comparison with Table 1 shows that additional efforts on non-CO_2 gases open the possibility to reach the 2°C target with a 3%/year rate of CO_2 emissions decrease after the peak, if climate sensitivity is equal to 3°C. It also allows to defer the peaking year by 4 to 7 years, in the case of a 4%/year rate of CO_2 emissions decrease after the peak, for the same 3°C climate sensitivity. This result illustrates the importance of measures on non-CO_2 gases to give some flexibility for the peaking of CO_2 emissions. For instance, Shindell et al. (2012) investigates in detail measures targeting methane and black carbon, which , combined with a scenario for CO2 emissions peaking just before 2020 and decreasing at 3%/year afterwards (the World Energy Outlook

2009 “450 ppm CO_2-equivalent” scenario; IEA, 2009), substantially reduces the risks of crossing the 2°C threshold.

Table 2. Link between the peaking year of emissions and the rate of emissions decrease after the peak, when efforts on non-CO2 gases are “doubled” compared to RCP3-PD, depending on the climate sensitivity. The range of peaking years given in each cell corresponds to the cases when emissions before the peak continue to grow at the 2005-10 rate (resulting in the lower bound for the peaking year) and when emissions before the peak are constant (resulting in the upper bound for the peaking year). ‘--‘ symbol means that there is no solution, i.e. the peak should already have happened.

	rate of decrease after peak					
Climate sensitivity	1%	2%	3%	4%	5%	6%
2°C	2029-2100	2038-2100	2043-2100	2047-2100	2050-2100	2052-2100
2.5°C	--	2018-2026	2024-2036	2029-2042	2032-2046	2034-2048
3°C	--	--	2014-2017	2019-2024	2022-2028	2025-2031
3.5°C	--	--	--	--	2013-2014	2015-2017
4°C	--	--	--	--	--	--
4.5°C	--	--	--	--	--	--

2.2.2. Negative emissions to save the day?

To include net negative global emissions in our “idealized” emissions trajectories, we reiterate the same simple exercise with a second set of emissions trajectories (Figure 3). They are identical to the first set until the peaking year for emissions, *n*, i.e. two scenarios are considered before peak, either with emissions (a) growing at the mean annual rate of emissions growth observed during 2005–10; or (b) fixed at their 2010 level. After emissions peak, however, they decrease linearly until 2100, by the amount *X* per year (expressed as a share of 2010 emissions).

Figure 3. Examples of the second set of Emission Trajectories, 2005–2100

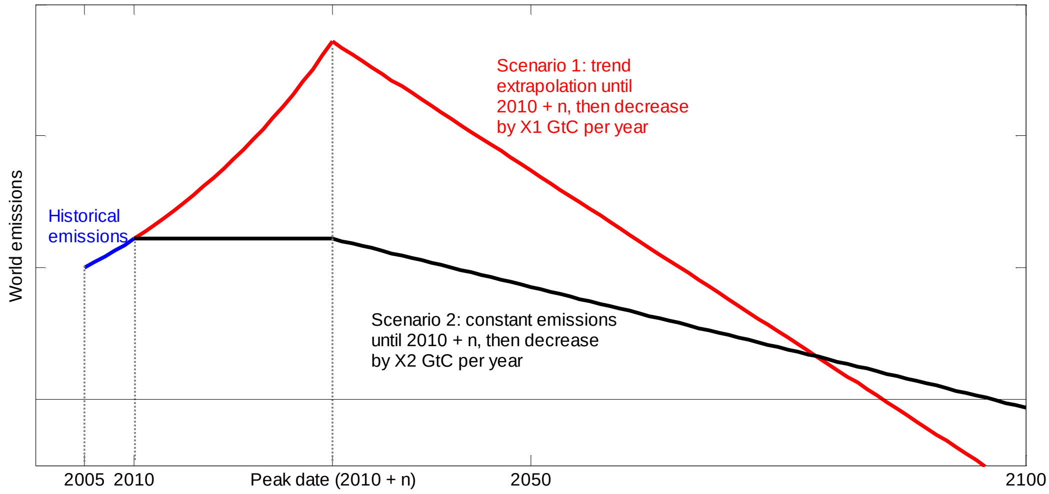
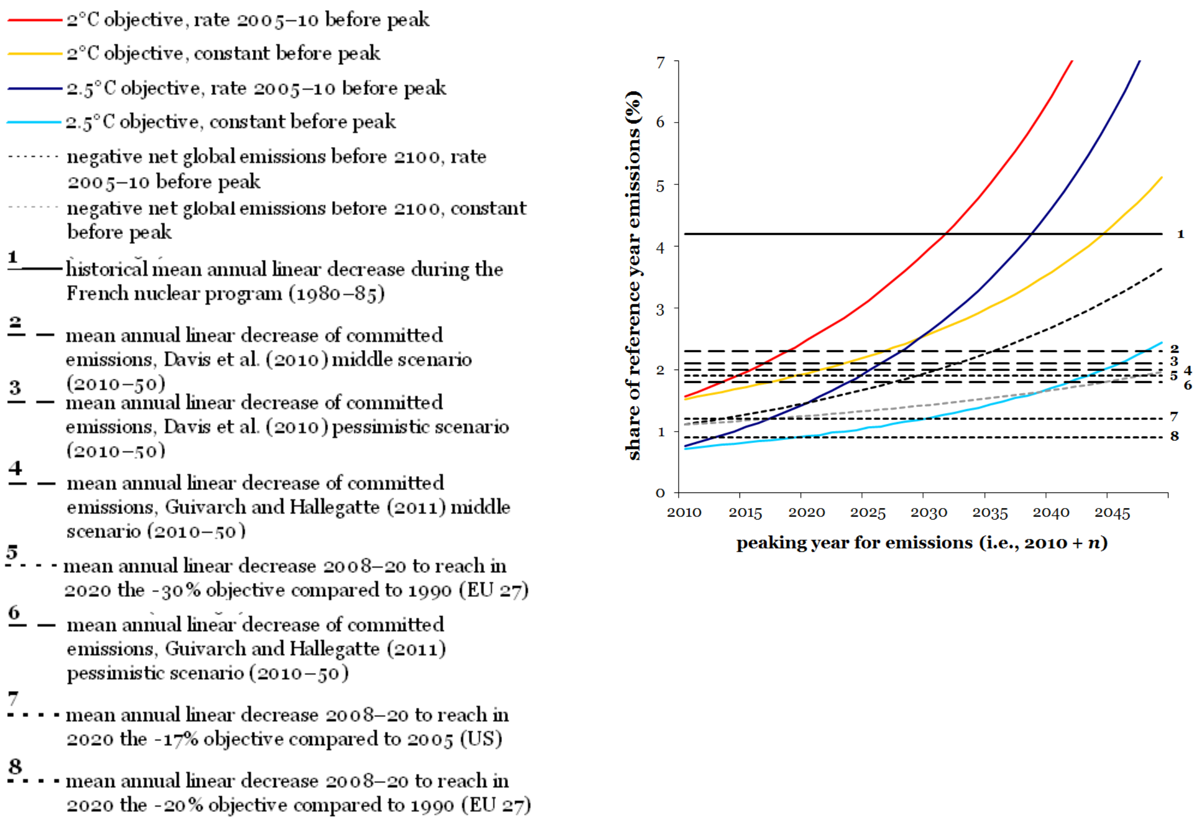


Figure 4 shows the linear annual decrease of emissions necessary to reach a 2°C target or a 2.5°C target as a function of the peaking year for emissions, if the radiative forcing from non-CO_2 gases and aerosols follows the trajectory from RCP3PD scenario. The figure also reports as horizontal lines the same points of reference as in previous exercise, converted to mean linear annual decreases as a share of reference years' emissions (1980 for the historical French data, 2010 for committed emissions from Davis et al. and Guivarch and Hallegatte (2011) analyses, 2008 for pledges). Additionally, the figure delimits the regions for which the combination of the peaking year and the linear annual decrease implies negative global emissions before the end of the 21st century. In particular it shows that - with climate sensitivity equal to 3°C - negative global emissions are necessary to reach the 2°C target, even if emissions peak today. Also, it shows that, if the peak date is between 2017 and 2026, depending on emissions trajectory before peaking year, a *global* annual decrease of the same order than EU high pledge may achieve the 2°C target. This corresponds to a linear decrease roughly equal to 2% of 2010 year emissions level, which would mean an absolute reduction of 0.7 $GtCO_2$ every year globally.

Figure 4. Linear Annual Decrease of Emissions, as a Share of 2010 Emissions, Necessary to Achieve the 2°C Target or a 2.5°C Target as a Function of the Peaking Year for Emissions, for a climate sensitivity equal to 3°C.



Of course, results are dependent on the climate sensitivity (Table 3). For a 2°C sensitivity, the 2°C target appears easier to reach: if global emissions are reduced by 0.7 $GtCO_2$ every year (i.e. 2% of 2010 emissions), emissions can peak after 2033, and in that case no negative global emissions are required. But if climate sensitivity is higher than 4°C, the room for maneuver is very limited and even if emissions were reduced annual by 2% of 2010 emissions from today on, the 2°C target would not be reached.

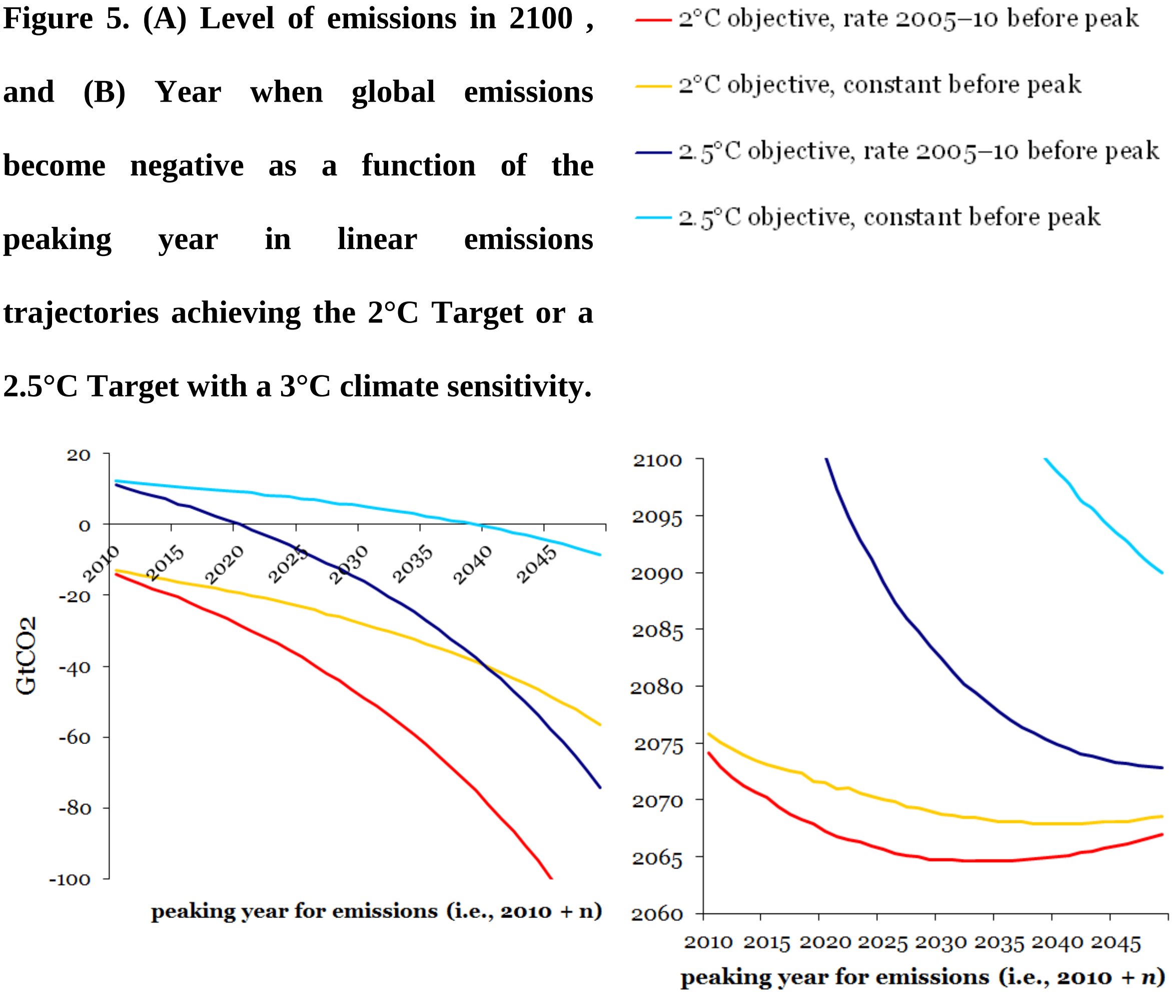
Table 3. Influence of the climate sensitivity on the link between the peaking year of emissions and the annual linear emissions decrease after the peak (expressed as a share of 2010 emissions). The range of peaking years given in each cell corresponds to the cases when emissions before the peak continue to grow at the 2005-10 rate (resulting in the lower bound for the peaking year) and when emissions before the peak are constant (resulting in the upper bound for the peaking year). '- -' symbol means that there is no solution, i.e. the peak should already have happened.

	annual decrease after peak (share of 2010 emissions)					
Climate sensitivity	1%	2%	3%	4%	5%	6%
2°C	2024-2065	2033-2074	2039-2077	2044-2080	2047-2081	2050-2082
2.5°C	--	2021-2033	2029-2045	2034-2051	2038-2056	2042-2059
3°C	--	2015-2021	2024-2035	2030-2043	2035-2048	2038-2052
3.5°C	--	2011-2012	2020-2027	2026-2036	2031-2042	2035-2047
4°C	--	--	2017-2022	2024-2032	2029-2038	2033-2043
4.5°C	--	--	2015-2019	2022-2029	2027-2036	2031-2041

At this point, it is interesting to assess the quantitative role played by negative global emissions in reaching the climate target. Figure 5 gives the year when global emissions become negative as a function of the peaking year (right panel) and the level of emissions in 2100 (left panel). It shows that negative emissions occur relatively late in the century (never before 2065), which may appear as good news since it gives some time for research, development and diffusion of technologies enabling such negative emissions.

But it also highlights that dramatically high levels of negative emissions may be needed. For instance, emissions need to reach -100% of current emission levels, i.e. around -35GtCO2, if peaking year is after 2025 and if emissions before peak continue to increase. These levels may seem unrealistically high, but they are partly due to the oversimplified form (linear) of emissions trajectories considered.

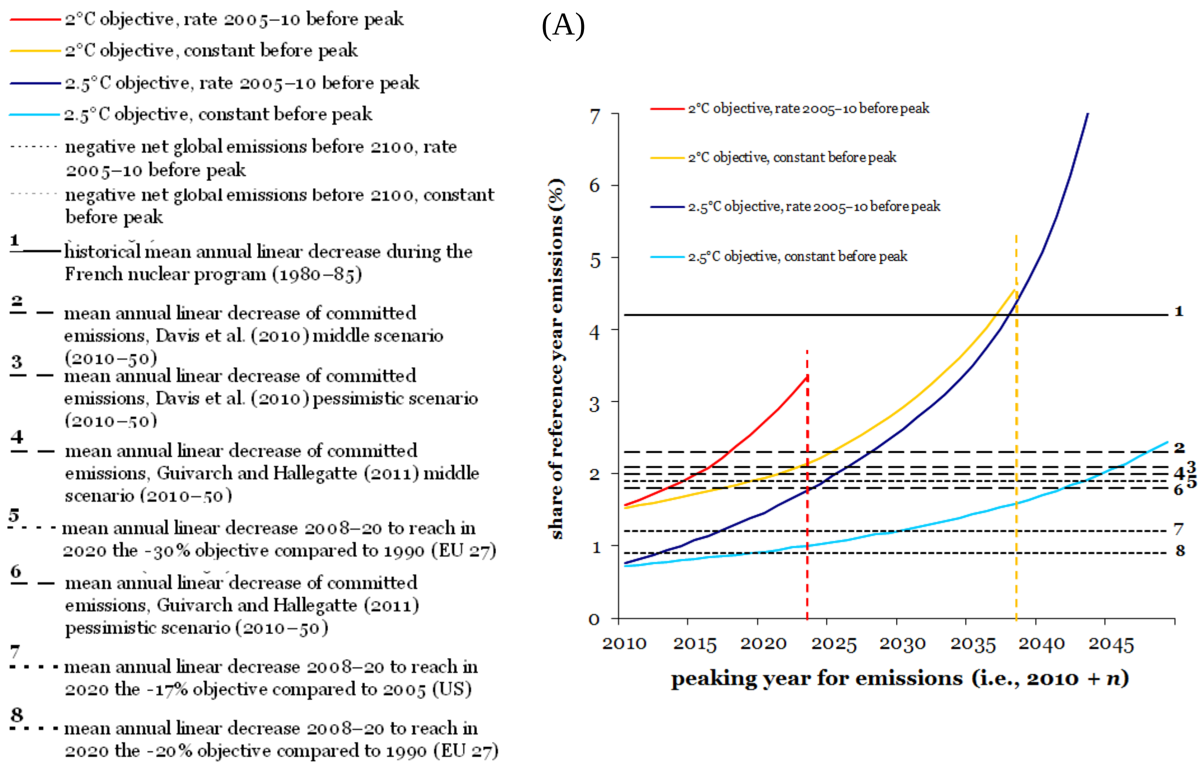
Figure 5. (A) Level of emissions in 2100 , and (B) Year when global emissions become negative as a function of the peaking year in linear emissions trajectories achieving the 2°C Target or a 2.5°C Target with a 3°C climate sensitivity.



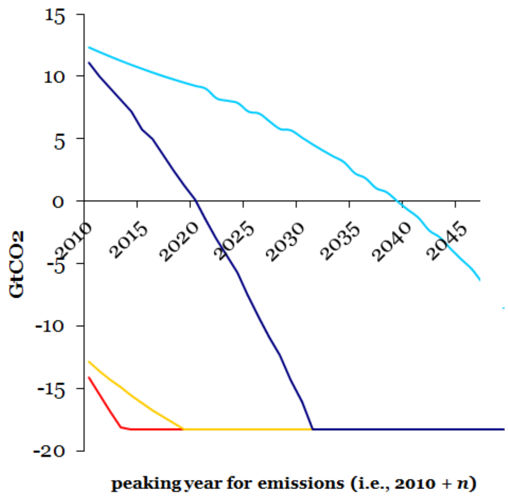
To account for possible limitations of the potential for net negative global emissions, a third set of idealized emissions trajectories is considered. Using the set of scenarios reviewed by van Vuuren and Riahi (2011), we assume that the earliest date of net global emissions becoming negative is 2060, and that the maximum negative emissions attained in 2100 is -5GtC (i.e. 18.33 $GtCO_2$). From these assumptions we delimit a linear maximum envelope for negative global emissions. Trajectories are then forced to remain within this maximum 2060-2100 envelope, and are assumed to follow a linear decrease from peak to 2060.

The graphs (Figure 6) are identical to those from previous experiment for the early dates of peaking year for emissions. But when the peak is delayed, the maximum envelope for negative emissions becomes binding, increasing the need for early emissions reductions between the peaking year and 2060. The linear reduction required to reach the 2°C target therefore increases more steeply with the peaking year than in the case without constraints on negative emissions.

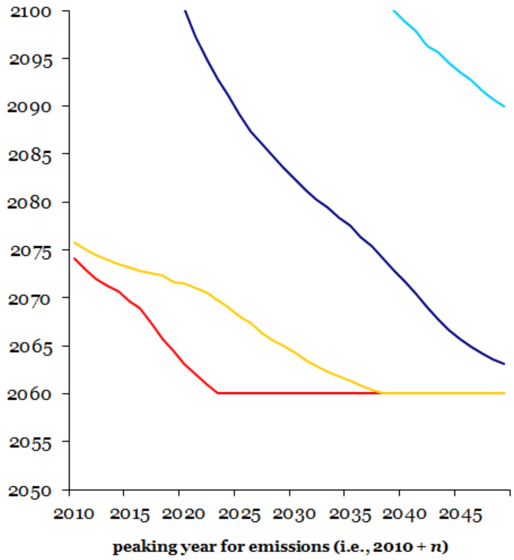
Figure 6. (A) Linear Annual Decrease of Emissions, as a Share of 2010 Emissions, Necessary to Achieve the 2°C Target or a 2.5°C Target as a Function of the Peaking Year for Emissions; (B) Level of emissions in 2100 ; and (C) Year when global emissions become negative as a function of the peaking year in linear emissions trajectories achieving the 2°C Target or a 2.5°C Target, with a 3°C climate sensitivity and when a maximum envelope for global negative emissions is taken into account.



(B)



(C)



If emissions peak occurs after a given date, it may even become impossible to find a trajectory of the form defined that respects the climate objective and the maximum envelope. E.g. for a 3°C climate sensitivity, reaching the 2°C target requires global emissions to peak before 2023 if emissions are assumed to keep growing before the peak. This result is obviously sensitive to the assumption on climate sensitivity. If only a little more pessimistic, e.g. considering a 3.5°C climate sensitivity, there is no trajectory of the form defined that respects the climate objective and the maximum envelope for global net negative emissions. In other terms, if climate sensitivity is equal to 3.5°C, the peaking year should already have happened to be able to reach the 2°C target with a linear emissions trajectory respecting the maximum envelope for global net negative emissions; see Table 4.

Table 4. Influence of the climate sensitivity on the link between the peaking year of emissions and the annual linear emissions decrease after the peak (expressed as a share of 2010 emissions), when there is a maximum envelop for negative emissions. The range of peaking years given in each cell corresponds to the cases when emissions before the peak continue to grow at the 2005-10 rate (resulting in the lower bound for the peaking year) and when emissions before the peak are constant (resulting in the upper bound for the peaking year). '- -' symbol means that there is no solution, i.e. the peak should already have happened.

	annual decrease after peak (share of 2010 emissions)					
Climate sensitivity	1%	2%	3%	4%	5%	6%
2°C	2024-2065	2033-2074	2039-2077	2044-2080	2047-2081	2050-2082
2.5°C	--	2021-2033	2028-2044	2032-2050	2034-2053	2036-2054
3°C	--	2015-2021	2020-2029	(--)-2033	--	--
3.5°C	--	--	--	--	--	--
4°C	--	--	--	--	--	--
4.5°C	--	--	--	--	--	--

Table 5 summarizes the results of the combination of the two strategies to "buy time", namely increasing the efforts on non-CO_2 gases and considering the potential for net negative emissions on the long-term. In that case, global CO2 emissions have to peak between 2017 and 2025 (depending on the emissions pathway before peaking year) if climate sensitivity is equal to 3°C and if global CO_2 emissions are reduced linearly by 0.7 $GtCO_2$ (i.e. 2% of 2010 emissions level) globally every year after the peak. The table also shows that this result is very sensitive to the assumptions on climate sensitivity and on the emissions decrease after the peak. The comparison between Table 5 and Table 4 shows that increasing the efforts on non-CO_2 gases allows to defer the peaking year by 2 to 4 years if climate sensitivity is equal to 3°C and if global CO_2 emissions are reduced linearly by 0.7 $GtCO_2$ (i.e. 2% of 2010 emissions level) globally every year after the peak.

Table 5. Influence of the climate sensitivity on the link between the peaking year of emissions and the annual linear emissions decrease after the peak (expressed as a share of 2010 emissions), when efforts on non-CO_2 gases are doubled. The range of peaking years given in each cell corresponds to the cases when emissions before the peak continue to grow at the 2005-10 rate (resulting in the lower bound for the peaking year) and when emissions before the peak are constant (resulting in the upper bound for the peaking year). '- - ' symbol means that there is no solution, i.e. the peak should already have happened.

		annual decrease after peak (share of 2010 emissions)					
Climate sensitivity	limit on negative emissions	1%	2%	3%	4%	5%	6%
2°C	no bound	2027-2100	2036-2100	2042-2100	2046-2100	2049-2100	2052-2100
	maximum envelope	2027-2100	2036-2100	2042-2100	2046-2100	2049-2100	2052-2100
2.5°C	no bound	2011-2015	2023-2039	2031-2049	2036-2055	2040-2059	2043-2062
	maximum envelope	2011-2015	2023-2039	2030-2049	2035-2055	2037-2058	2039-2060
3°C	no bound	--	2017-2025	2026-2038	2031-2046	2036-2051	2039-2054
	maximum envelope	--	2017-2025	2024-2036	2027-2040	(--)-2042	(--)-2043
3.5°C	no bound	--	2012-2016	2021-2030	2028-2039	2033-2045	2036-2049
	maximum envelope	--	2011-2012	--	--	--	--
4°C	no bound	--	--	2019-2025	2025-2034	2030-2040	2034-2045
	maximum envelope	--	--	--	--	--	--
4.5°C	no bound	--	--	2016-2021	2023-2031	2028-2037	2032-2042
	maximum envelope	--	--	--	--	--	--

Here again, it is not possible to give an unequivocal answer whether the possibility to produce negative net global emissions makes the 2°C target reachable. It depends on the climate sensitivity, the stringency of CO_2 emissions reductions achievable (technically feasible and economically, socially and politically acceptable), the reductions achievable for non-CO_2 gases and the extent of negative emissions possible at the end of the century. However, increased efforts on non-CO2 gases and the possibility to produce negative net global emissions in 50 years both give some flexibility in the peaking year and/or in the stringency of emissions reductions after the peak necessary to reach the 2°C target.

2.3. Concluding on the feasibility of the 2°C target?

The conclusion of these simple exercises is that the 2°C target can only be reached if climate sensitivity is not too high, and either under optimistic assumptions about available technologies allowing for negative emissions in 50 years or under the combination of two conditions, namely: (a) an immediate change in mitigation policies with universal participation, leading global emissions to peak rapidly, and (b) the possibility − in particular the economic, social and political acceptability − to reproduce at the global scale and over several decades the highest rate of emissions reductions ever observed in a country over a short period. Obviously, the analysis above presents important caveats: the carbon cycle and climate models are very simplified and emissions trajectories considered are very stylized. More complex carbon cycle and climate models, and less idealized emissions trajectories evaluated with complex Integrated Assessment Models would give different numbers, but no significant qualitative differences. Studies using carbon cycle and climate models of intermediate-complexity come to similar conclusions: Huntingford et al. (2012), using a version of MAGICC model, conclude that "*the slowest rate of decarbonization consistent with a 50% chance of exceeding 2°C to be slightly below 3% per annum, where this corresponds to the specific case of emissions peaking by year 2014 (so in fact deviation from business-as-usual would have to have already started) and a zero emissions floor*", and Friedlingstein et al. (2011), using Bern2.5D model, conclude that "*For a median climate sensitivity, a long-term 90% emission reduction relative to the present-day level is incompatible with a 2°C target within the coming millennium. Zero or negative emissions can be compatible with the target if medium to high emission-reduction rates begin within the next two decades. For a high climate sensitivity, however, even negative emissions would require a global mitigation rate at least as great as the highest rate considered feasible by economic* *models to be implemented within the coming decade. Only a low climate sensitivity would allow for a longer delay in mitigation action and a more conservative mitigation rate, and would still require at least 90% phase-out of emissions thereafter*."

These results are also consistent with published emissions scenarios using Integrated Assessment Models. Rogelj et al. (2011) show that in the set of scenarios with a 'likely' (greater than 66%) chance of staying below 2°C, emissions peak between 2010 and 2020. Van Vuuren and Riahi (2011) show that these scenarios, while indicating the absence of a direct relationship between short-term emissions and long-term stabilization targets, suggest that reaching the 2°C target with 2020 emissions above 2000 levels is possible only if negative global emissions are achieved in the second half of the century.

Published modeling experiments exploring low stabilization all reach the first conclusion that stabilization of greenhouse gas concentrations at levels compatible with the 2°C target is feasible (e.g. Edenhofer et al., 2010; van Vuuren et al., 2010). However, their second conclusion, that it is feasible only under a set of optimistic assumptions, should not be ignored. For example, van Vuuren et al. (2010) indicate that the low stabilization levels compatible with the 2°C target are close to the maximum achievable emissions reduction potential in their model. They show that the target is achievable only if optimistic assumptions are adopted on (a) the early participation of major sectors and regions in sufficiently stringent mitigation policies from 2013 onward; (b) the expansion of the area needed for food production to allow space for bio-energy; (c) a significant increase in the efficiency of second-generation biofuels; and (d) the carbon neutrality of bio-energy, that is, that large-scale development of bio-energy can be done without an increase in land-related CO_2

emissions (from soil degradation, shifting cultivation, deforestation, or draining of peat lands) and without an increase of nitrous oxide emissions from the application of fertilizer.

It should also be noted that failed experiments tend to not be published, which introduces a bias in the low stabilization literature (Tavoni and Tol, 2010). Indeed, when a stringent target is revealed as infeasible with a given model, it simply does not appear in the literature. Often the policy demand for evaluations of the 2°C target has pushed modelers toward implementing more optimistic assumptions for their mitigation portfolios (such as the introduction of large-scale Biomass-Energy with Carbon Capture and Storage).

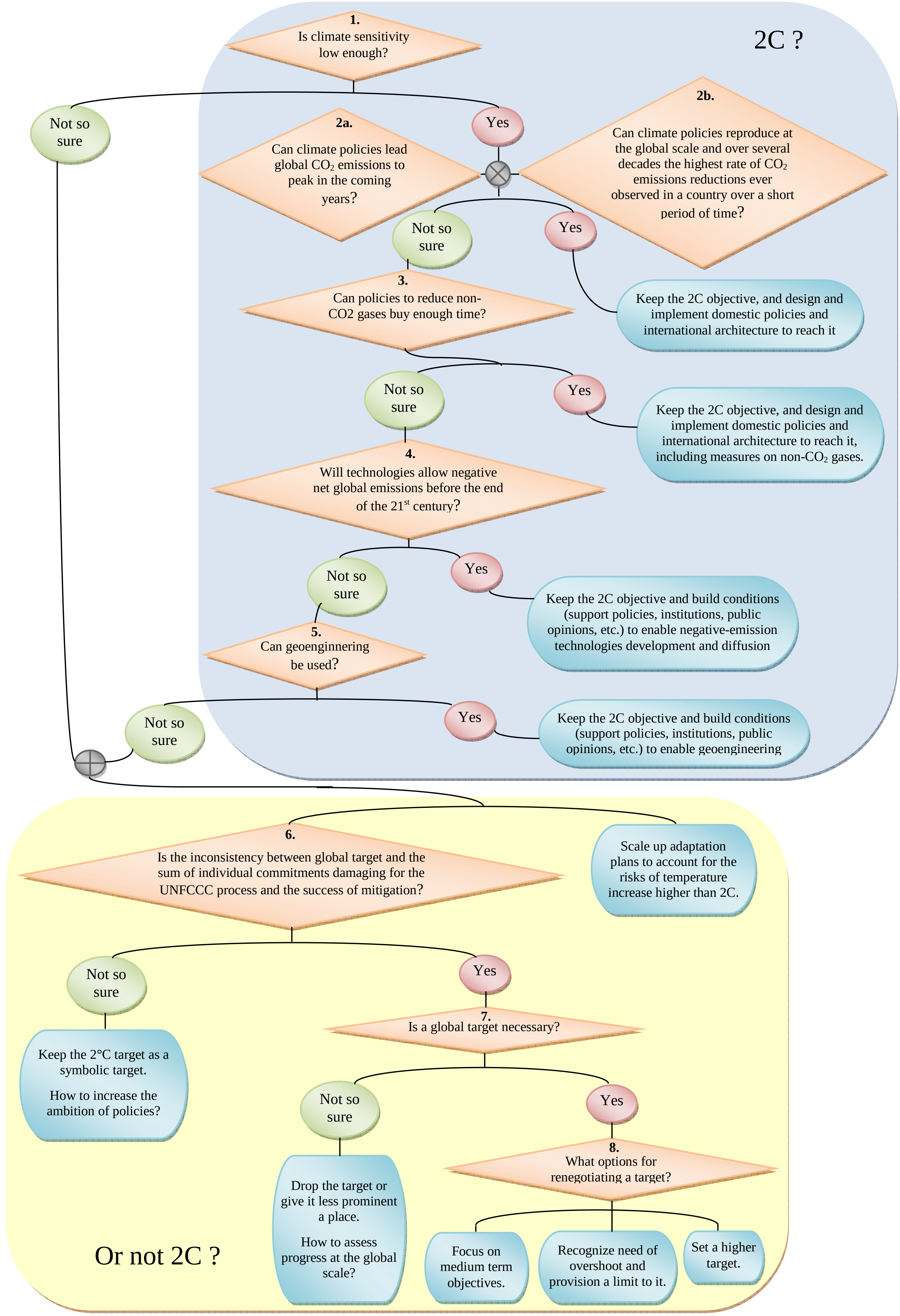
Finally, it should be highlighted that most analyses evaluate the feasibility of the 2°C target on the basis of technical feasibility only. When accounting for possible political, economic, or social constraints, the feasibility appears considerably lower. For instance, the Energy Modeling Forum 22 results showed that delayed participation of non-Annex I countries in mitigation agreements, as an application of the "differentiated responsibilities" and "respective capabilities" principles of the UNFCCC, makes the 450 ppm CO_2-eq target unreachable (Clarke et al., 2009). Anderson and Bows (2011) even conclude that the 2°C target without an overshoot of the target is no longer compatible with economic prosperity.

Our contribution to this literature is to provide a simpler but more exhaustive exploration of the link between the peak year, the achievable emissions reductions, the possibility for negative emissions and climate sensitivity. And we do so with a simple model avoiding the black-box effect of larger Integrated Assessment Models.

3. From beliefs to actions

The analysis above does not allow to conclude from a scientific point-of-view, since there remain points of inherent uncertainty in the evidence and differences in world views that influence what one defines as “achievable”. This forces eventually some subjectivity in the decision. In the same way, the role of the 2°C objective can be discussed: Is it a binding commitment from the international community to the world population? Or is it a non-binding symbolic goal to help international negotiations move forward? Figure 7 draws an “uncertainties and decisions tree” to explicit the alternative view points and their implications. The figure organizes the points of deep uncertainty (i.e. the points that are not reducible to objective probability distributions, and thus imply eventually subjectivity in answering them) in a series of questions, and summarizes the implications of the alternative answers given to these questions. It is separated into blocks: the first explores the deep uncertainty points involved in the question “Is the 2°C target achievable?” (or in other words “Can we stay in a 2°C world?”), while the second investigates the points involved in the question “What to do with a target that is not achievable?”.

Figure 7. “Uncertainties and decisions tree” to explicit the alternative view points and their implications. Diamond-shaped forms correspond to questions on which there is deep uncertainty, and therefore imply eventually subjectivity in answering them. Oval-shaped forms give the implications ensuing from answering to the deep uncertainty elements.


2C ?
1.
Is climate sensitivity low enough?
Not so sure
Yes
2a.
Can climate policies lead global CO_2 emissions to peak in the coming years?
2b.
Can climate policies reproduce at the global scale and over several decades the highest rate of CO_2 emissions reductions ever observed in a country over a short period of time?
Not so sure
Yes
Keep the 2C objective, and design and implement domestic policies and international architecture to reach it
3.
Can policies to reduce non-CO2 gases buy enough time?
Not so sure
Yes
Keep the 2C objective, and design and implement domestic policies and international architecture to reach it, including measures on non-CO_2 gases.
4.
Will technologies allow negative net global emissions before the end of the 21st century?
Not so sure
Yes
Keep the 2C objective and build conditions (support policies, institutions, public opinions, etc.) to enable negative-emission technologies development and diffusion
5.
Can geoenginnering be used?
Not so sure
Yes
Keep the 2C objective and build conditions (support policies, institutions, public opinions, etc.) to enable geoengineering
6.
Is the inconsistency between global target and the sum of individual commitments damaging for the UNFCCC process and the success of mitigation?
Scale up adaptation plans to account for the risks of temperature increase higher than 2C.
Not so sure
Yes
Keep the 2°C target as a symbolic target.
How to increase the ambition of policies?
7.
Is a global target necessary?
Not so sure
Yes
Drop the target or give it less prominent a place.
How to assess progress at the global scale?
8.
What options for renegotiating a target?
Focus on medium term objectives.
Recognize need of overshoot and provision a limit to it.
Set a higher target.
Or not 2C ?

The first deep uncertainty to be resolved to answer whether the 2°C target is achievable, is the value of climate sensitivity (Figure 7, question 1). Note that, in an analytical study of the link between the peak and the cumulative anthropogenic CO_2 emission Raupach et al. (2011) also find that the climate sensitivity is the main uncertainty influencing this link, followed, in decreasing order, by the uncertainties on non-CO_2 radiative forcing, on the effects of climate change on CO_2 fluxes and on the effects of increasing CO_2 on the partition of anthropogenic carbon. Although scientific understanding and confidence in quantitative estimates of climate sensitivity have increased substantially, it is still not possible to estimate a unique and reliable density function of climate sensitivity (IPCC 2007, WG I, Box 10.2). This difficulty arises mainly from the fact that small uncertainties in (positive) feedbacks involved in climate processes (in particular, those associated with clouds) are highly amplified in the resulting climate sensitivity (Roe and Baker, 2007).

Answering "no" to the question "Is the climate sensitivity low enough?" may well directly lead out of the 2°C world. If it is not possible to give a precise threshold value to define what "low enough" means, evidences suggest that for a climate sensitivity of 4°C, there is very little room for manoeuvre and the target seems already out of reach.

Then the second deep uncertainty point is the ability of climate policies to reduce emissions. If one believes that ambitious climate policies will be able to lead global CO_2 emissions to peak in the coming years (Figure 7, question 2a) and to reproduce at the global scale and over several decades the highest rate of emissions reductions ever observed in a country over a short period of time (Figure 7, question 2b), it "only" remains to design and implement these "ambitious climate policies" at the local and national scales and the international architecture to support them. But obviously behind the opinion on the possible and acceptable level of climate policies stringency, there are in fact alternative world views on intergenerational equity and on the definition of prosperity for instance. See for example the lively debate on the discount rate to be used for climate change (notably Nordhaus, 2007; Weitzman, 2007; Dasgupta, 2008; Dietz and Stern, 2008), this discount rate determining how much should be spent now to reduce emissions in order to have benefits (avoided climate damages) for future generations. See as well Jackson (2009) for a definition of prosperity that is contrasting with the prevailing vision that prosperity is synonym to economic growth. What is considered achievable from a political and economic perspective is and will remain a subjective question (theoretically, one can stop emitting overnight by turning off all emitting devices).

Analyses indicate that measures reducing non-CO_2 gases would allow to "buy time" for the peaking year of CO_2 emissions (see section 2.2.1 above and Shindell et al. (2012) for instance). The remaining uncertainty is whether these measures can buy enough time to allow reaching the 2°C target (Figure 7, question 3).

In the same way, if one believes that technologies will allow net negative global emissions before the end of the 21st century to a scale that will put the 2°C target within reach (Figure 7, question 4), it "only" remains to set the conditions (support policies, institutions, public acceptability…) for the development and diffusion of these technologies. However this possibility to achieve net negative global emissions remains uncertain. Current knowledge suggests that it would require large-scale combinations of bio-energy and carbon capture and storage (BECCS) (Blanfrd et al., 2009; van Vuuren et al., 2010a; Edenhofer *et al., 2010;* van Vuuren et al., 2010b; Azar et al., 2010). However, BECCS is not currently a commercially proven technology and its large-scale development raises a number of issues. The potentials of large-scale biomass production and large-scale CCS remain controversial, and the (un)sustainability of the underlying biomass sourcing is a major concern. The technical potential of biomass production remains controversial and difficult to characterize (IPCC SRREN, 2011), due to large uncertainty on a range of issues including yield growth possibilities, the production potential of degraded land and climate change feedbacks. Moreover, large-scale biomass production would increase competition for use of land and water resources among food, bioenergy, timber, conservation or other uses, with potential undesirable effects on water availability, food security, soil quality, biodiversity and subsistence farming (Landis et al., 2008; Tilman et al., 2009). In addition, the sustainability (or not) of the underlying biomass sourcing is critical. Life-cycle analyses demonstrate that in some situations the overall impact of biomass on GHG emissions can be potentially higher than the direct emissions of conventional fuels, depending on the use of fertilizers, the input of fossil fuels in the production, transport and conversion of biomass, as well as on how land use is affected by the biomass production (see Leemans et al., 1996; Searchinger et al., 2008; Fargione et al., 2008). Another critical issue for large-scale BECCS is the potential to store carbon from both fossil fuels and bioenergy. An IPCC assessment (2005) reports storage capacity in geological formations of the order of 2 000 GtCO2 to 3 600 GtCO2, depending on uncertainties with respect to storage capacities in saline formations in particular. However, realizing this potential may encounter obstacles – physical or political – and it is still controversial whether there are sufficient safe geological storage options, and sufficient political acceptability, for CCS to work at a large scale. In particular, leakage rates are a major concern for the development of CCS (Ha-duong and Loisel, 2008).

These concerns call for further evaluations of the potential of large-scale BECCS and the associated risks and trade-offs. They also indicate that a strategy assuming the possibility of large-scale BECCS is uncertain.

Without negative emissions, the remaining solutions to achieve the 2°C target would rely on geo-engineering strategies (Figure 7, question 5) with carbon dioxide removal techniques or radiative-forcing management techniques. These technologies are even more uncertain than BECCS: their technical feasibility is barely proved, and there are major unknowns regarding their effectiveness, costs and environmental impacts (IPCC, 2007, WGIII, chapter 11, section 11.2.2; The Royal Society, 2009). Recent prominent reviews have emphasized that geo-engineering strategies entail significant risks of negative side effects and that serious and complex governance issues would have to be resolved before geo-engineering could be used (Schneider, 2008; Barrett, 2008). There would probably be (negative) transboundary effects involved in geo-engineering schemes, and potential winners and losers. The issue of who should decide to implement geo-engineering, when and how is an unresolved challenge for international governance. Even research on such geo-engineering schemes entails dilemmas because of its potential unintended effects, and the fear that commitment to geo-engineering would undermine efforts to deal with the cause of the original problem, i.e. the anthropogenic emissions of greenhouse gases in the atmosphere (Cicerone, 2006; Lawrence, 2006). Most recent reviews, however, recommend expanding research on geo-engineering to acquire more knowledge on the various technologies, but emphasize the need for a process for ensuring global transparency and cooperation in such research (Blackstock and Long, 2010).

If one believes that the answers to all previous points are negative, the 2°C target becomes unreachable, at least without allowing for an overshoot of the target, and may be considered as unrealistic. In that case, the 2°C target does not seem compatible with the sum of individual countries commitments, and an internal inconsistency appears in the Copenhagen and Durban climate agreements.

The first conclusion concerns adaptation: adaptation plans designed assuming a temperature rise of 2°C are likely to be insufficient, and adaptation plans, infrastructure design, and land use and urban plans need to consider the possibility of greater warming. Research should also be directed toward the assessment of stronger warming and its impact, and of adaptation options in this case.

Then, there is a question on what to do with a 2°C target that becomes increasingly difficult to achieve. Some inconsistency between the target and the commitments is probably unavoidable given the nature of the evolution of international negotiations on climate change. Indeed, such negotiations have been built on two parallel tracks since the Bali Road Map in 2007. The first is a Kyoto-like top-down track that starts from a common global objective, such as the 2°C objective, and tries to derive consistent commitments for all parties (country burden sharing). This approach stems from the public good nature of the climate change issue, for which only global emissions matter. It was adopted from the start of international negotiations on climate change, but gave rise to unsolvable disputes about the burden sharing rules and negotiations deadlocked. This deadlock entailed the creation of a second track of negotiations.

This second track is a bottom-up track based on a pledge-and-control approach, and is the basis of the Copenhagen Accord. This approach corresponds to the political economy of the realities of climate change negotiations: mitigating climate change requires ambitious domestic policies with potentially large economic impacts, which cannot be decided in absence of internal negotiations within each country. Country commitments are thus difficult to set up through a burden sharing negotiations in short UNFCCC sessions. A bottom-up track through which countries announce commitments is thus extremely useful. However, this track cannot be sufficient, since these unilateral commitments need at one point to be added up and assessed on the basis on their aggregated effect on the world climate, compared to an objective in terms of global climate change.

Today, the world is reaching the point when the inconsistency between the global 2°C objective and individual countries' commitments is becoming very obvious. But there is no consensus on whether this inconsistency is damaging the UNFCCC process and ultimately the success of climate mitigation (Figure 7, question 6).

An unreachable target may be damaging by creating unrealistic expectations and an impression of failure, obscuring real successes in limiting emissions, creating a demobilizing climate of pessimism. Clemens et al. (2007) warn about this risk for Millennium Development Goals (MDGs). They argue that the growing concern that the MDGs will not be achieved by 2015 is obscuring the bigger picture that development progress has been occurring at unprecedented levels over the past years. Indeed, among the many countries that are likely to miss the MDGs in 2015, many will yet still outperform the historical trajectories of now-developed countries. They conclude that, by labelling many development successes as failures, the MDGs may create an inaccurate climate of pessimism toward aid, which may undermine future constituencies for aid (in donors) and reform (in recipients).

Also, the inconsistency between global target and country commitments may give low emitting and highly vulnerable countries, such as Small Island Developing States or African countries, the impression that high emitting countries behave opportunistically. These countries could then lose trust in the process. More generally, trusting interstate relationships can emerge only when states can ‘commit’ themselves to particular outcomes (e.g., Kydd, 2000; Wendt, 1999), through commitments that are sufficiently costly to violate (Kydd, 2000; Fearon, 1994; Schelling, 1966). And the ability to make binding commitments is essential to the process of international institutionalization (Keohane, 1984). Making unrealistic commitments suggests that violating them is not costly, and weaken all other commitments, and trust in general.

The consequences of a loss of trust in international negotiation can be illustrated by the case of international development aid. Since 1970, developed countries have repeated their commitment to increase aid up to 0.7 percent of their gross national product. Yet in most countries, it has amounted to only 0.4 percent. The 0.7 percent target likely played a positive role to obtain public support for foreign aid budget in developed countries. But because of the continued gap between the target and the reality, it also had a negative impact on international discussions, as developing countries now understandably receive all commitments related to development aid by the industrial countries with disappointment, and sometimes skepticism.

Similarly, within countries, citizens and businesses are unlikely to support an international process that appears inconsistent and based on unrealistic commitments. National climate policies thus risk to appear less credible (or acceptable), and citizens and private actors would be less inclined to invest in low-carbon options, which would reinforce the risk of lock-in a carbon-intensive economic model.

But this opinion is not consensual. Alternative points of view consider the 2°C target as a “symbolic target”, i.e. a target that is more a mean than an end. In that framework, the 2°C target becomes a tool, a process to generate discussion, focus attention, assign accountability, and measure progress. Along this view of the 2°C target as primarily a mean to drive mitigation efforts worldwide, its inclusion in official texts, in particular the final UNFCCC text adopted in Durban in December 2011, may be acknowledged as a real success, and renegotiating it would be damaging to the process. The Millennium Development Goals provide an example of such symbolic targets that are not supposed to be binding constraints, but as a commonly-agreed objective guiding the action of many governments, donors, and international organizations. The MDG offered a framework that undoubtedly helped reverse aid decline after end of Cold War, and stimulate the aid community (Hulme, 2007; Hulme and Scott, 2010). With such a target, the increasing difficulty in reaching the target might not be a problem, except if a "literal" interpretation of the target creates a demobilizing impression of failure (as suggested by Clemens et al.,2007).

Depending on what one thinks about this debate, i.e. about the damage from the inconsistency between the global target and individual country commitments, the best approach is different.

If one thinks that the damage is limited, then it is possible to keep the 2°C target as a symbolic target, and focus on improving country commitment to close the gap. If one thinks that the damage is large, then the international community should prevent a widening of the gap between the official global target and the sum of countries' commitments. There are several ways to do so.

First, one can think that such a global target is not necessary (Figure 7, question 7). In that case, it might be possible to drop it or give it less prominent a place, without any other changes.

Otherwise, assuming that a realistic long-term global target is useful or even necessary, the international community would have to set a new, more realistic objective. There are alternative possibilities to change the international target (Figure 7, question 8). It can be done through an increase in the objective (e.g., to 2.5°C), through the recognition that an overshoot will be needed and the provision of a limit to this overshoot (e.g., the objective of a 2°C stabilization with overshoot below 2.5°C), or through a focus on medium-term objectives (e.g. the objective of limiting warming below 1.8°C in 2050).

Such a change in target would likely be perceived as a failure, especially by those who have championed the 2°C target for years, but it would issue a useful wake-up call, and would also be a way to communicate an important aspect of the climate change problem: delaying action does not mean we can still achieve the same results later. If we delay the construction of a high speed train line by five years, we get the same train line, or an even better one, five years later. By contrast, with climate change mitigation, reachable objectives will become increasingly less attractive over time.

4. Conclusion: 2C or not 2C?

This paper does not pretend to answer on the feasibility of the 2°C target or on what should be done with this target as it becomes increasingly difficult to achieve. Instead it acknowledges there are several points of deep uncertainty involved when exploring these two questions. It thus aims at providing the reader with simple visualizations and an “uncertainties and decisions tree” to disentangle the points of deep uncertainty and investigate their link with policies and options to move forward on climate change. This “tree” shows that the possibility to remain in a 2°C world depends on a series of uncertainties on (i) whether the climate sensitivity is “low enough”, (ii) whether climate policies can lead global CO_2 emissions to peak in the coming years and can reproduce at the global scale and over several decades the highest rate of CO_2 emissions ever observed in a country over a short period of time, (iii) whether policies to reduce non-CO_2 give more flexibility for CO_2 emissions, (iv) whether technologies would allow negative net global emissions before the end of the 21st century and (v) whether geo-engineering could be used. Leaving a 2°C world also entails uncertainties for policies. What should be done with a target increasingly difficult to reach depends (i) on whether the inconsistency between the global target and the sum of individual commitments is damaging for the UNFCCC process and the success of mitigation, and (ii) on the status of the target (literal vs. symbolic).

This large number of points of deep uncertainty call for two things. First, more research is needed to provide further evidences on these points to better inform decision making. Second, one has to acknowledge that some uncertainty will inevitably remain, and that subjectivity and differences in world views will inescapably be involved, therefore we need frameworks for communicating and decision making under deep uncertainty (see for instance Kandlikar et al., 2005; Hall et al., 2012).

In this perspective, this article aims at providing information to make it possible for the reader to make his or her own opinion. And this is why we let our readers draw their own conclusion from this information…

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Annex

This Annex describes the hypotheses and modeling assumptions used to produce the figures and tables in Section 2 of the article.

Radiative Forcing from Other Gases

The radiative forcing from other gases follows the trajectory from the scenario Representative Concentration Pathway 3 Peak&Decline (RCP3-PD) from the IMAGE model (van Vuuren *et al.*, 2011). This scenario is representative for the scenarios leading to extremely low greenhouse gas concentration levels in the literature. It represents a substantial reduction of greenhouse gases over time and is a best-case scenario with respect to non-carbon dioxide (CO_2) emissions. Details on individual pollutants emissions trends (SO_2, CO, NH_3, NO_x, VOC, Black Carbon and Organic Carbon) are given in van Vuuren *et al.* (2011).

Carbon Cycle Model and Climate Model

The carbon cycle is a three-box model, after Nordhaus and Boyer (2010). The model is a linear three-reservoir model (atmosphere, biosphere + ocean mixed layer, and deep ocean). Each reservoir is assumed to be homogenous (well-mixed in the short run) and is characterised by a residence time inside the box and corresponding mixing rates with the two other reservoirs (longer timescales). Carbon flows between reservoirs depend on constant transfer coefficients. GHGs emissions (CO2 solely) accumulate in the atmosphere and they are slowly removed by biospheric and oceanic sinks.

The stocks of carbon (in the form of CO_2) in the atmosphere, in the biomass and upper ocean, and in the deep ocean are, respectively, *A*, *B*, and *O*. The variable *E* is the CO_2 emissions. The evolution of *A*, *B*, and *O* is given by

$$\frac{dA}{dt} = -\phi_C^{A,B} + E,$$
$$\frac{dB}{dt} = \phi_C^{A,B} - \phi_C^{B,O}, \text{ and}$$
$$\frac{dO}{dt} = \phi_C^{B,O};$$

The fluxes are equal to

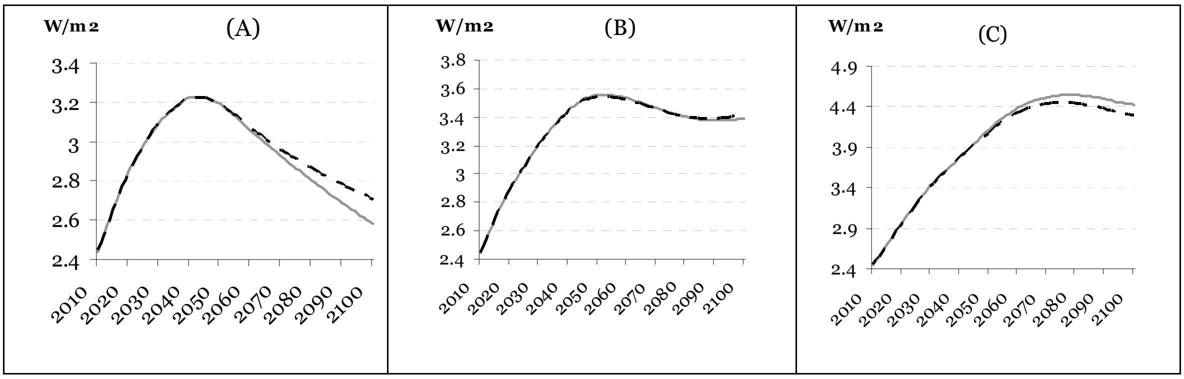
$$\phi_C^{A,B} = a_{21}A - a_{12}B, \text{ and}$$
$$\phi_C^{B,O} = a_{23}B - a_{32}O;$$

The initial values of *A*, *B*, and *O*, and the parameters a_{12}, a_{21}, a_{23}, and a_{32} determine the fluxes between reservoirs. The main criticism which may be addressed to this C-cycle model is that the transfer coefficients are constant. In particular, they do not depend on the carbon content of the reservoir (e.g. deforestation hindering biospheric sinks) nor are they influenced by ongoing climatic change (e.g. positive feedbacks between climate change and carbon cycle).

Nordhaus original calibration has been adapted to reproduce data until 2010 and results from IMAGE model for a given trajectory of CO2 emissions (see below), giving the following results (for a yearly time step): a12= 0.02793, a21=0.03427, a23=0.007863, a32=0.0003552, with the initial conditions: A2010=830 GtC (i.e. 391ppm), B2010=845 GtC and O2010=19254 GtC.

Figure A1, panel B, compares the trajectory of total radiative forcing calculated with the three-box carbon cycle model and the IMAGE model forced with the emissions trajectory used for calibration. This emissions trajectory, from Energy Modeling Forum 24 study, is between those of RCP 3PD and RCP 4.5 from RCP database. Panels A and C compares the three-box carbon cycle model and IMAGE model results for the RCP 3PD and the RCP 4.5 emissions trajectories, respectively. The differences are linked to elements modifying transfer coefficients, such as reforestation or deforestation for instance, not accounted for in the three-box model with constant transfer coefficients. For information the three emissions trajectories A, B and C lead to a temperature increase in 2100, using the simplified carbon-cycle and climate model presented here, of 1.9°C, 2.4°C and 2.9°C, respectively.

Figure A1. Trajectories of total radiative forcing calculated with the three-box carbon cycle model (dashed black lines) and IMAGE model (solid grey line) for three given emissions trajectories: (A) the RCP 3-PD emissions trajectory, (B) the emissions trajectory used for calibration, from EMF24 study, between those of RCP 3-PD and RCP 4.5, and (C) the RCP 4.5 emissions trajectory.



The additional forcing caused by CO_2 and non-CO_2 gases is given by

$$F_A = F_{2X} \frac{\log\left(\frac{A}{A_{PI}}\right)}{\log 2} + F_{non-CO_2},$$

where A_{PI} is the pre-industrial CO_2 concentration (280 ppm), F_{2x} is the additional radiative forcing for a doubling of the CO_2 concentration (3.71 W.m^{-2}), and F_{non-CO_2} is the additional radiative forcing of non-CO_2 gases.

The temperature model is a two-box model, after Schneider and Thompson (1981) and Ambrosi *et al.* (2003), with the atmosphere temperature T_A and the ocean temperature T_O as follows:

$$\frac{dT_A}{dt} = \sigma_1\left(-\frac{F_{2X}}{T_{2X}}T_A - \sigma_2\phi_T + F_A\right),$$

$$\frac{dT_O}{dt} = \sigma_3\phi_T, \text{ and}$$

$$\phi_T = T_A - T_O,$$

where T_{2x} is the equilibrium temperature increase at the doubling of the CO_2 concentration, that is, it represents climate sensitivity. All parameters have been calibrated to reproduce results from CMIP5 fromCNRM-CERFACS global climate model, CNRM-CM5, over the 21st century for RCP3-PD and RCP4.5 radiative forcing trajectories (using a least squares method). This calibration leads to the following parameter values for heat transfer rates (for a yearly time step): σ_1= 0.054C.W^{-1}.m^2, σ_2= 0.664 C^{-1}.W.m^{-2} and σ_3= 0.0308, and a climate sensitivity of 2.6°C. When varying the climate sensitivity parameter to test the sensitivity of results to this parameter in Section 2 of the article, heat transfer rates are kept constant, equal to the calibration values.

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